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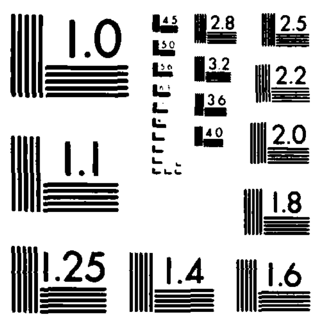
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Final Report

on

IGNITION AND UNSTEADY FLAME PROPAGATION IN TURBULENT REACTIVE FLOWS

by

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Contract No.: DAAG-29-80-C-0123
Project No.: 1L161102BH57-06

Research supported by the U.S. Army Research Office and monitored under the technical supervision of Drs. Robert E. Singleton and David M. Mann, Engineering Sciences Division, Army Research Office

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A136 450
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) IGNITION AND UNSTEADY FLAME PROPAGATION IN TURBULENT REACTIVE FLOWS	5. TYPE OF REPORT & PERIOD COVERED FINAL REPORT 10 MAY 1980-31 OCT. 1983
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) TAU-YI TOONG	8. CONTRACT OR GRANT NUMBER(s) DAAG-29-80-C-0123
9. PERFORMING ORGANIZATION NAME AND ADDRESS MASSACHUSETTS INSTITUTE OF TECHNOLOGY DEPARTMENT OF MECHANICAL ENGINEERING CAMBRIDGE, MA 02139	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 1L161102BH57-06
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. ARMY RESEARCH OFFICE POST OFFICE BOX 12211 RESEARCH TRIANGLE PARK, NC 27709	12. REPORT DATE DECEMBER, 1983
	13. NUMBER OF PAGES 24
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report) UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

TURBULENT FLAME PROPAGATION
TURBULENCE-COMBUSTION INTERACTIONS
THERMAL STRUCTURE
SPECTRAL DISTRIBUTIONS
INSTABILITY MECHANISMS

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A CONCEPTUAL MODEL WAS DEVELOPED FOR THE STUDY OF TURBULENT FLAME PROPAGATION. COMPARISON OF MEASURED APPARENT TURBULENT-FLAME-PROPAGATION SPEEDS WITH LIMIT CURVES DERIVED ON THE BASIS OF THIS MODEL INDICATED THE IMPORTANCE OF RATE AUGMENTATION WITHIN THE TURBULENT FLAME STRUCTURE. SPECTRAL CHANGES OBSERVED IN THE THERMAL STRUCTURE OF PREMIXED METHANE-AIR V-FLAMES STABILIZED BEHIND A CYLINDRICAL FLAMEHOLDER INDEED SHOWED THE EXISTENCE OF REACTION-AUGMENTED TURBULENCE IN THE SMALLER EDDIES, WHICH WOULD ACCOUNT FOR THE INCREASE IN THE PROPAGATION SPEEDS.

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This report summarizes the main results and conclusions obtained in a research program on turbulent flame propagation, conducted at the Massachusetts Institute of Technology with the support of the U.S. Army Research Office under Contract DAAG-29-80-C-0123. Detailed information may be found in the publications listed in the Bibliography (Appendix I).

Several important questions which remain unresolved in the study of turbulent combustion are related to turbulence-combustion interactions — whether they exist or not, what is their nature and what are the governing mechanisms. The main objective of this research program is to examine these turbulence-combustion interactions.

A conceptual model was developed for the study of turbulent flame propagation. Comparison of measured apparent turbulent-flame-propagation speeds with limit curves derived on the basis of this model indicated the importance of rate augmentation within the turbulent flame structure. Spectral changes observed in the thermal structure of premixed methane-air V-flames stabilized behind a cylindrical flameholder indeed showed the existence of reaction-augmented turbulence in the smaller eddies, which would account for the increase in the propagation speeds. These results will be described briefly below.

(1) Conceptual Model

Turbulence effects on flame propagation was examined by Damköhler[1*] in a carefully executed experimental investigation on bunsen flames.

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*Superscript numbers indicate publications listed in the References.

His view of analyzing the effects according to different turbulence scales and intensities is still basically sound and promises better understanding with further pursuit along this avenue. In general, for low intensities, eddies larger than the laminar-flame thickness cause flame wrinkling and thereby increase the turbulent-flame-propagation speed through area increase, whereas smaller eddies enhance flame-propagation speed by augmenting the energy- and mass-transport rates.

Except at very high turbulence intensities, when it is possible to observe disruption of wrinkled flame fronts and "islands" of unburned mixture being engulfed and burned through turbulent mixing with the hot products of combustion, the apparent turbulent-flame-propagation speed based on an arbitrary area can be derived by the simultaneous consideration of the effects of large- and small-scale turbulence. A conceptual model was formulated on this basis by the principal investigator[2] for the study of turbulent flame propagation. It was noted that the apparent turbulent-flame-propagation speed can be obtained as the product of two terms; one is due to the augmentation of transport rates of energy and mass and of effective reaction rates within the flame structure and the other, due to the increase in the flame area resulting from wrinkling*. Limit expressions were developed for estimating the maximum possible increase in the apparent turbulent-flame-propagation speed due to either rate-augmentation or wrinkling alone. They are shown as dashed curves in Fig. 1 together with the experimental results of Damköhler[1] and Williams

*Similar ideas were advanced by Povinelli and Fuhs[3] and Gökalp[4]. Nevertheless, they suggested the two effects to be additive rather than multiplicative. Also, their limit expressions were different.

and Bollinger[5], in terms of the ratio of the apparent turbulent-flame-propagation speed to the laminar speed versus the burner-diameter Reynolds number. The top curve is for rate augmentation only and the bottom, for flame wrinkling only. Note that almost all the measured results lie somewhere between the two limits, implying the importance of rate augmentation within the flame structure over the entire range. Furthermore, Toong[2] noted that the top curve lies above an extensive collection of data given in fig. 5 of Andrews et al.[6], thus representing the maximum possible turbulent-flame-propagation speed obtainable. One also notes from Fig. 1 the rather small effect on the propagation speed due to wrinkling alone. In other words, increase in flame area due to wrinkling is not sufficient by itself to account for the observed increase in the apparent turbulent-flame-propagation speeds.

(2) Turbulence-Combustion Interactions

The question of flame-generated turbulence, an aspect closely related to turbulence-combustion interactions, has remained unresolved for many years. Karlovitz et al.[7] in 1951 introduced the idea to explain the observed discrepancies between the measured and the predicted values of turbulent-flame-propagation speed. However, definitive demonstration of its existence was lacking. On the other hand, Summerfield et al.[8] proposed a model based on distributed reaction zone and Gökalp[9] suggested a more general concept of flame-turbulence interaction. Our measurements on premixed V-flames, in fact, showed very little temperature fluctuations in the hot products but much larger amplitudes of higher-frequency fluctuations within the flame brush. Apparently, the discrepancies observed by Karlovitz et al. were due to inadequate accounting of the turbulence effect simply on the basis of flame wrinkling. As shown in Fig. 1, they should have also included the effect due to rate augmentation which arises from the presence of smaller eddies within the flame brush.

In order to study the turbulence-combustion interactions, detailed spectral changes in the thermal structure of premixed methane-air V-flames stabilized behind a cylindrical flameholder were examined in this program. Instantaneous temperatures were measured across the flame brush by the use of 25 μm-diameter, frequency-compensated, Pt/Pt-10% Rh thermocouples at different equivalence ratios and different distances from the flameholder. Turbulence-generating grids of different mesh size were placed at the burner exit in order to investigate the effects of turbulence scale and intensity on the turbulence-combustion interactions.

Figure 2 shows the results for a lean quasi-laminar flame (equivalence ratio $\phi = 0.75$) when there was no turbulence-generating grid at the burner exit. Each column presents the all-pass, high-pass (50 Hz) and low-pass (50 Hz) signals at a given distance downstream from the flameholder. As the thermocouple was moved across the flame brush from the unburned side (downward in Fig. 2 for each of the three columns), temperature fluctuations started to appear with accompanying increase in the mean temperature. Within the flame brush, fluctuations of larger amplitudes and higher frequencies were observed. In the burned gases, however, fluctuations were essentially absent, implying the importance of chemical reaction rate within the reaction zone in triggering and sustaining these fluctuations.

It is to be noted that for this flame configuration, even though there was no turbulence-generating grid at the burner exit, one still expects chemical reaction to interact with turbulence generated by the flameholder and in the shear layer between the hot gases and the unburned mixture.

Near the flameholder (at 3 mm downstream as shown in Fig. 2), the amplitudes of the temperature fluctuations across the flame brush were rather small. As the observation station was moved farther downstream (at 35 and 70 mm, Fig. 2), the flame brush became thicker with accompanying increase in the amplitudes of the temperature fluctuations, suggesting possible development of instabilities due to the evolution of chemical reaction within a flame kernel as it moved downstream from the recirculation zone behind the flameholder.

The amplitudes and the frequencies of these temperature fluctuations were found also to depend on the equivalence ratio, thus implying again they were due to turbulence-combustion interactions.

Similar results were observed for turbulent V-flames in the presence of turbulence-generating grids of 4, 10 and 20 mesh at the burner exit, except that the amplitudes of the higher-frequency fluctuations were much larger. Figure 3 shows the results with a 4-mesh grid. Note again the changes of these fluctuations within the flame brush from the cold to the hot side and also with increasing distance downstream. Effect of equivalence ratio on the flame structure was also observed.

Correlation of simultaneous signals from two thermocouples spatially separated at a fixed distance apart indicated the presence of low-frequency fluctuations (lower than 20 Hz), which led to flame motion, drifting back and forth (cf. low-pass signals in Figs. 2 and 3).

Figures 4 and 5 show the distributions of the apparent mean temperature and RMS temperature fluctuations across the flame brush at different distances downstream of the flameholder and at different equivalence ratios for quasi-laminar and turbulent flame, respectively. The maximum RMS value was found to occur at a position where the gradient of the apparent mean temperature was near maximum. Note again the evolution of the turbulence-combustion interactions with increasing distance downstream. Also, note the effects due to the equivalence ratio and also the presence of turbulence-generating grids of different mesh size at the burner exit.

The development of the peak RMS temperature fluctuations with increasing distance downstream of the flameholder is shown in Fig. 6 for quasi-laminar and turbulent flames (with 4-mesh grid) at different equivalence ratios. Both all-pass and high-pass (20 Hz) signals were compared. The effects of the equivalence ratio were clearly indicated. In general, the peak fluctuations were greater for higher (lean) equivalence ratios, except that the effect was more complicated for the high-pass signals for the case with 4-mesh grid, implying possible complex turbulence-combustion interactions in different spectral regions.

As suggested by Damköhler[1], rate augmentation is mainly due to eddies smaller than laminar-flame thickness while flame wrinkling is due to larger eddies. Thus, it is important to examine changes in the spectral distribution due to the presence of turbulence grids. Figure 7 shows a comparison of the spectral density distribution of mean-square temperature fluctuations* for the quasi-laminar (when there was no turbulence grid at the burner exit) and the turbulent case (with 4-mesh grid) at a position within the flame where the all-pass RMS temperature fluctuations were the maximum. Due to the presence of grid turbulence, an increase of nearly two-orders of magnitude was observed in the spectral densities within the higher-frequency region (100-500 Hz), despite almost equal values in the lower-frequency region. This comparison clearly shows a significant increase in the intensities of the smaller eddies (or eddies of higher frequencies), thus leading to an increase in the turbulent-flame-propagation speeds.

Spectral density distributions of mean-square temperature fluctuations are shown in Fig. 8 for different positions within a turbulent flame brush (with 10-mesh grid) at a fixed distance downstream of the flameholder. The one nearest to the burned region (position D) was the lowest and the one somewhere intermediate between the hot products and the unburned mixture (position B) was the highest. (Note the two-decade difference in the spectral densities.) Significant values were also monitored near the unburned region (posotion A), presumably due to flame drifting at the lower frequencies and turbulence generated by the flameholder and the 10-mesh grid. Somewhat lower values were observed at position C nearer to the burned region than position B. This figure thus suggests that the degree of the turbulence-combustion interactions depends on the reaction rate at different positions within the flame brush (cf. inset in Fig. 8

*Integrated area under the curve between two specific frequencies represents the mean-square temperature fluctuations within the band pass.

for the corresponding distributions of apparent mean temperature and RMS temperature fluctuations).

Figure 9 shows that the spectral densities were rather low at all frequencies near the flameholder ($z' = 3$ mm) and increased with distance downstream ($z' = 35$ and 70 mm). However, they seemed to attain some fully-developed values downstream, as much as two-orders-of-magnitude increase over the values upstream. This observation implies that the turbulent structure depends on interactions of rate processes, presumably due to the coupling between chemical kinetics and turbulence, thus leading to the observed temporal development.

The spectral distributions were also different at different equivalence ratios and for different mesh sizes of the turbulence-generating grid. All these observations indicate strongly that it is important to examine the spectral distribution in order to identify the mechanisms governing turbulence-combustion interactions in different frequency bands.

(3) Instability Mechanisms

Despite lack of full justification, the results obtained seem to indicate the relevance of different instability mechanisms in governing the turbulence-combustion interactions in different frequency bands. They include hydrodynamic instability for the low-frequency fluctuations and coupling between chemical kinetics and turbulence for the higher-frequency components. Due to the presence of the low-frequency fluctuations which led to slow motion of the flame across the monitoring station, the long-time signals obtained at a given spatial position in the laboratory-reference coordinates did not originate from a fixed position within the flame brush. One should thus exercise extreme care in the analysis of these results in the different frequency bands.

In order to shed light on the nature of the higher-frequency components at different "instantaneous" mean temperatures within the flame brush, the signals should be analyzed within time intervals much shorter than the characteristic time of the low-frequency instability. One can then relate these fluctuations to the chemical effect at an instantaneous mean temperature pertaining to this time interval and the corresponding reaction rate and infer therefrom whether they are due to the coupling between turbulence and chemical kinetics on the basis of our understanding of the instability mechanisms in reacting flows.[10]

Figure 10 shows a comparison of the RMS temperature fluctuations within the high-frequency region at different instantaneous mean temperatures (pertaining to a time-interval of 5 to 20 ms versus a characteristic time of 200 ms for a low-frequency fluctuation of 5 Hz) for a turbulent flame (with 4-mesh grid) and a quasi-laminar flame (without grid-generated turbulence). Despite some scatter, Fig. 10 shows that the RMS temperature fluctuations were the highest within the reaction zone and lower near the unburned and the burned regions (consistent with the observations in Figs. 2-5 and 8). Also consistent with Fig. 7, the RMS temperature fluctuations were higher for the turbulent flame. Even though the comparison in Fig. 10 lends some support to the postulation that the higher-frequency fluctuations are augmented by chemical reaction, further work still needs to be done to elucidate the details of the mechanism governing the coupling between turbulence and chemical kinetics.

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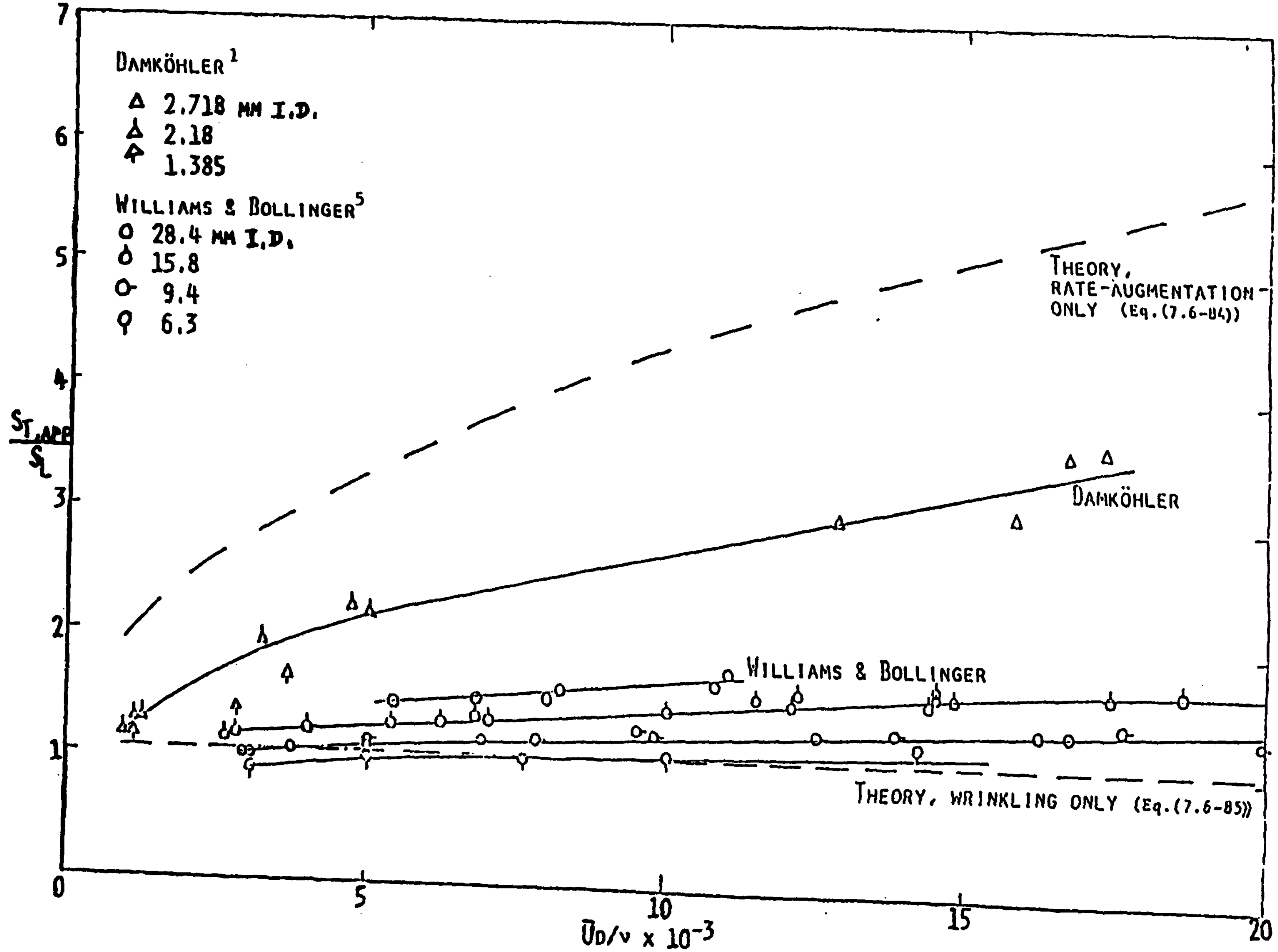


FIG. 1 RATIO OF APPARENT TURBULENT TO LAMINAR FLAME-PROPAGATION SPEEDS VERSUS THE DIAMETER REYNOLDS NUMBER, SOLID CURVES - EXPERIMENTAL, DASHED CURVES - THEORETICAL, ACCORDING TO EQS. (7.6-84) AND (7.6-85)[2]

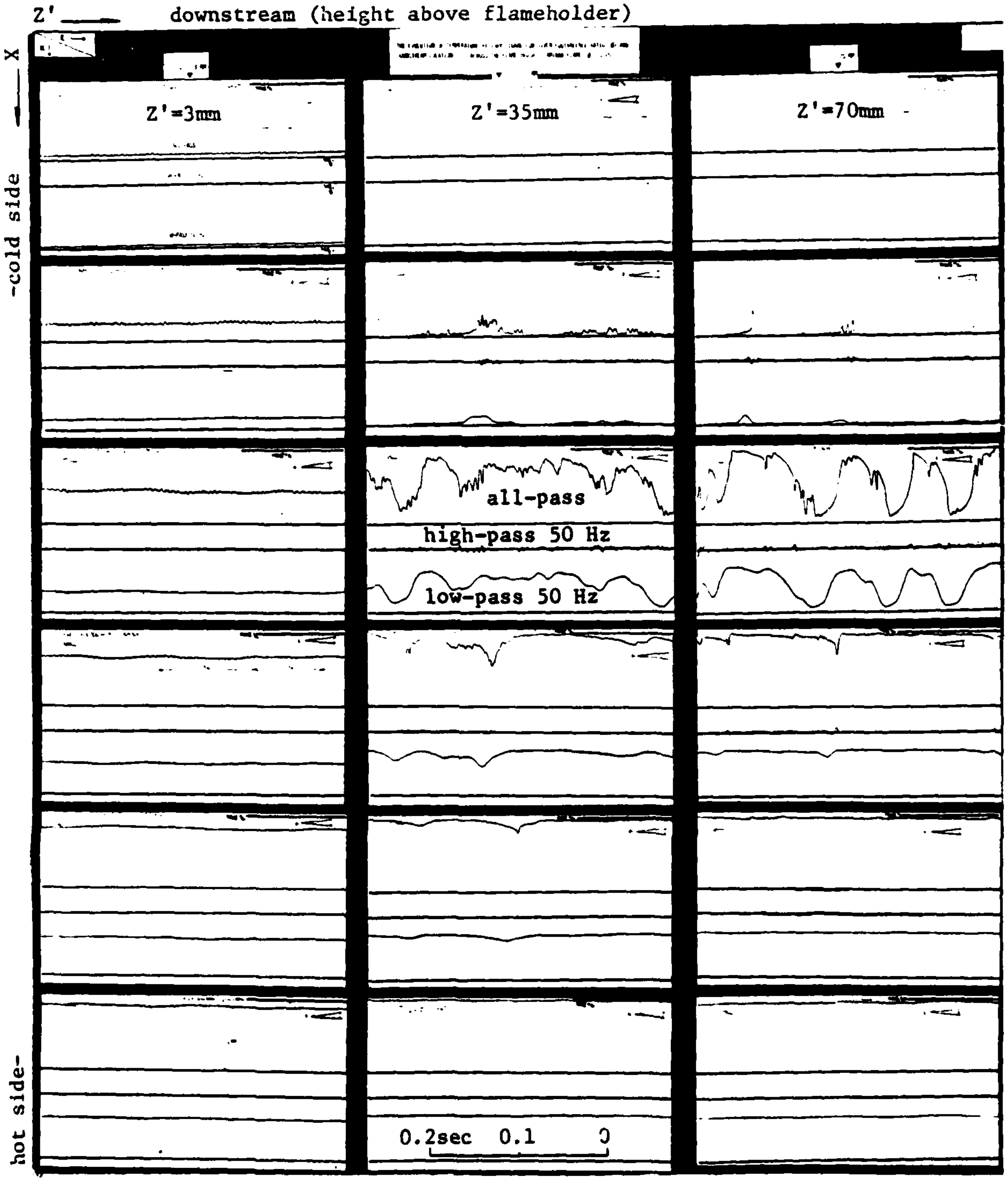


FIG. 2 TEMPERATURE SIGNAL FOR GIVEN EQUIVALENCE RATIO (ϕ) AND DOWNSTREAM LOCATION (Z') ACROSS THE FLAME BRUSH - QUASI-LAMINAR FLAME, ϕ = 0.75, MEAN VELOCITY = 2.4 m/s

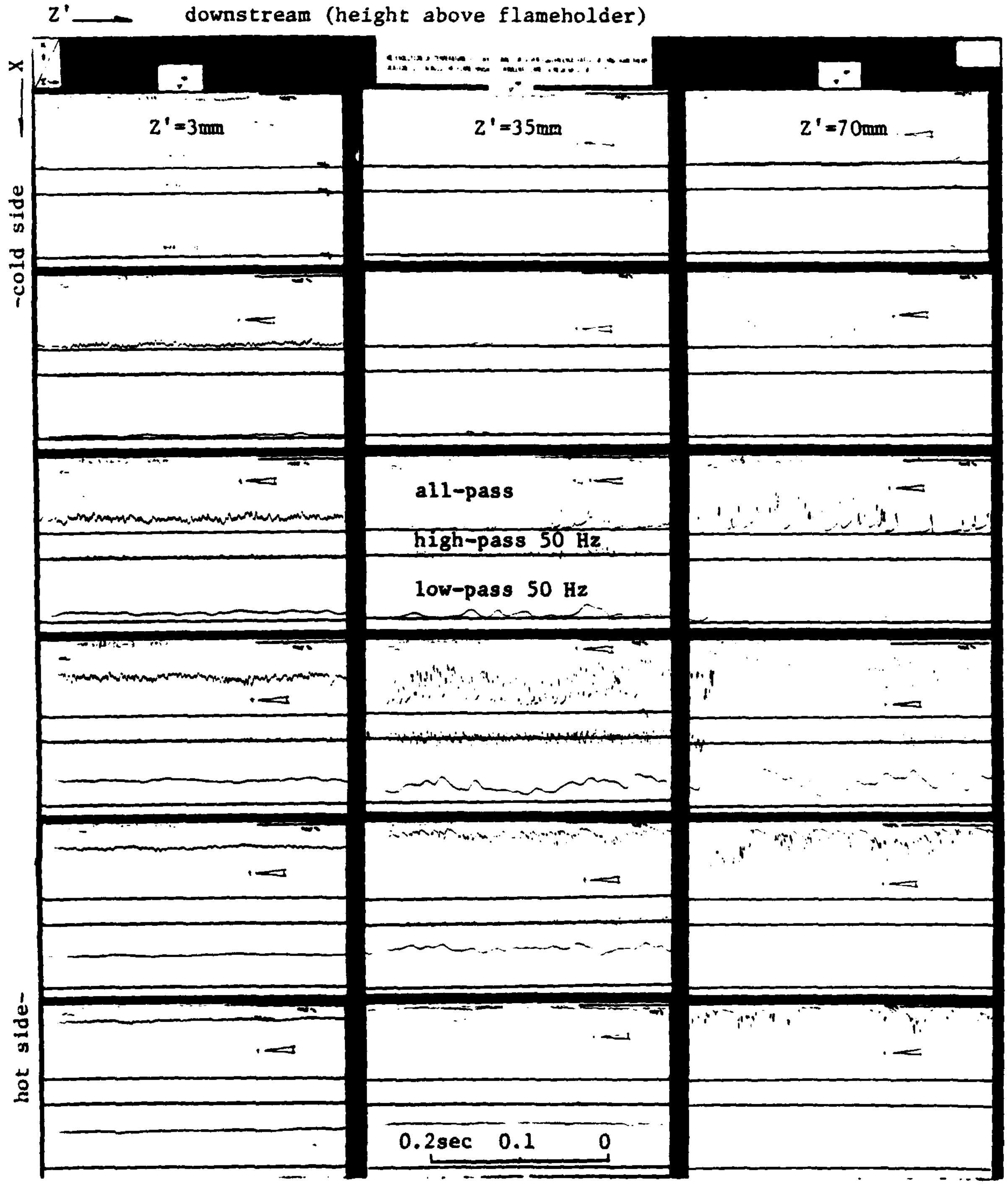
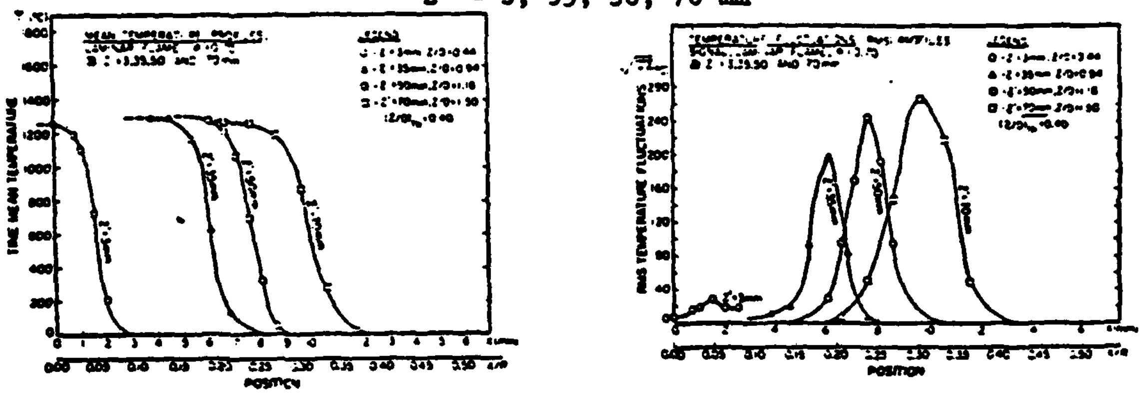


FIG. 3 TEMPERATURE SIGNAL FOR GIVEN EQUIVALENCE RATIO (ϕ) AND DOWNSTREAM LOCATION (Z') ACROSS THE FLAME BRUSH - TURBULENT FLAME, 4-MESH GRID, ϕ = 0.75, MEAN VELOCITY = 2.4 m/s

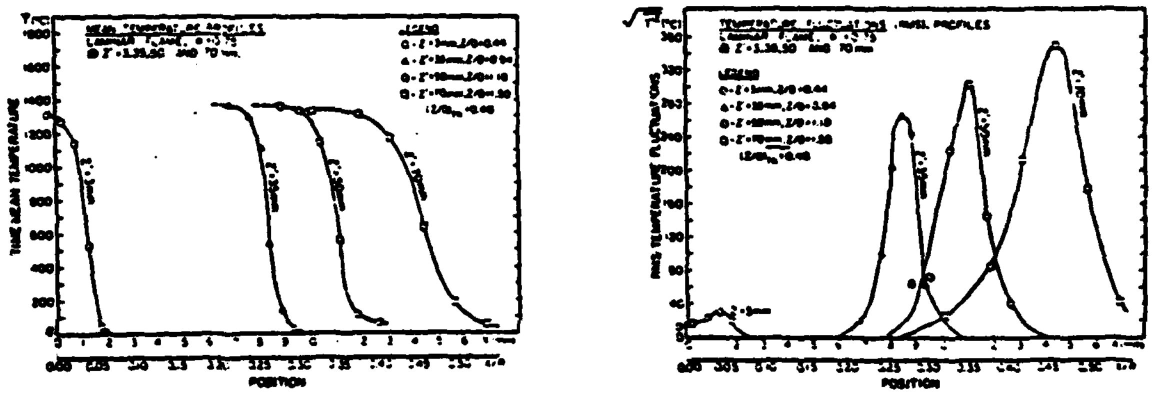
Ø = 0.70

Z' = 3, 35, 50, 70 mm



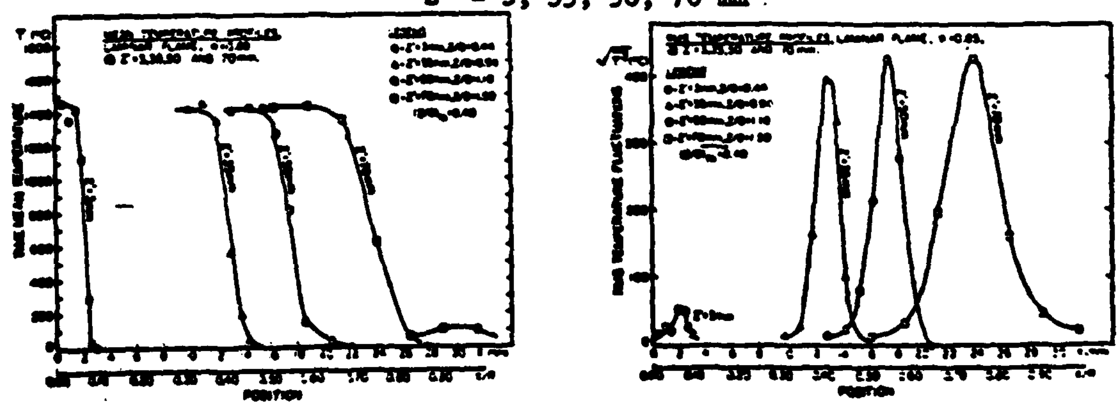
Ø = 0.75

Z' = 3, 35, 50, 70 mm



Ø = 0.85

Z' = 3, 35, 50, 70 mm

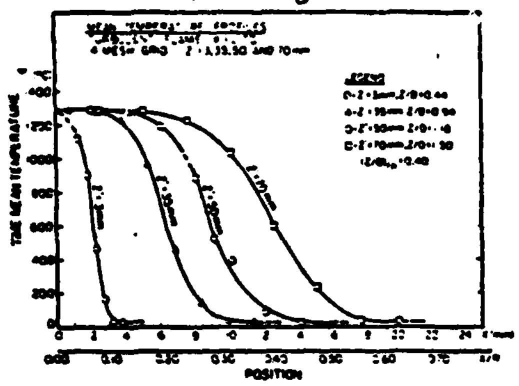


time-mean rms

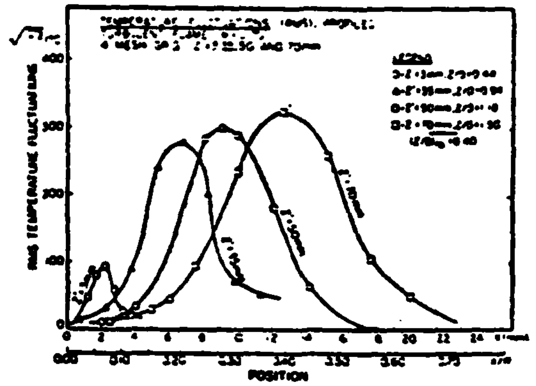
FIG. 4 DISTRIBUTION OF APPARENT MEAN TEMPERATURE AND RMS TEMPERATURE FLUCTUATIONS - QUASI-LAMINAR FLAME, MEAN VELOCITY - 2.4 m/s

Ø = 0.70

4 mesh grid

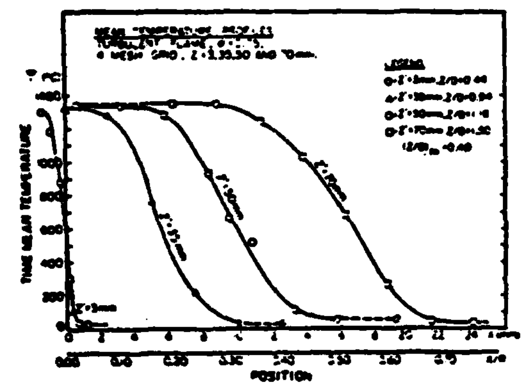


Z' = 3, 35, 50, 70 mm

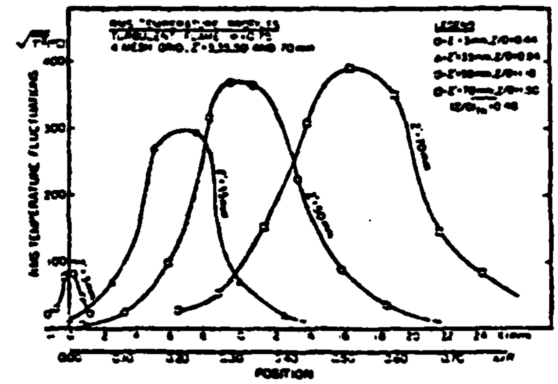


Ø = 0.75

4 mesh grid

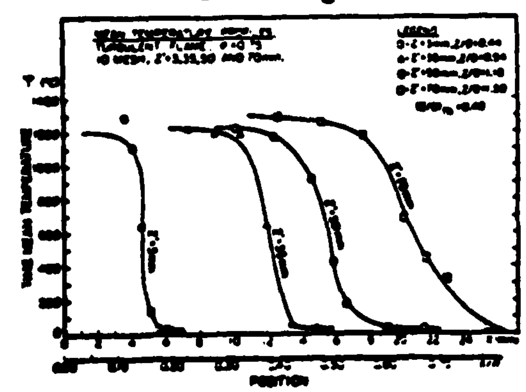


Z' = 3, 35, 50, 70 mm

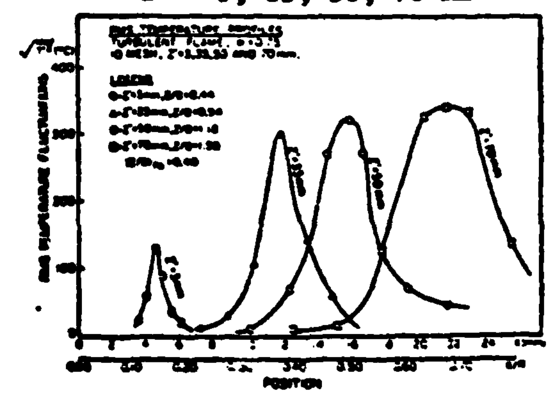


Ø = 0.75

10 mesh grid



Z' = 3, 35, 50, 70 mm



time-mean

rms

FIG. 5 DISTRIBUTION OF APPARENT MEAN TEMPERATURE AND RMS TEMPERATURE FLUCTUATIONS ACROSS THE FLAME BRUSH - TURBULENT FLAME; 4-MESH GRID AND 10-MESH GRID, MEAN VELOCITY = 2.4 m/s

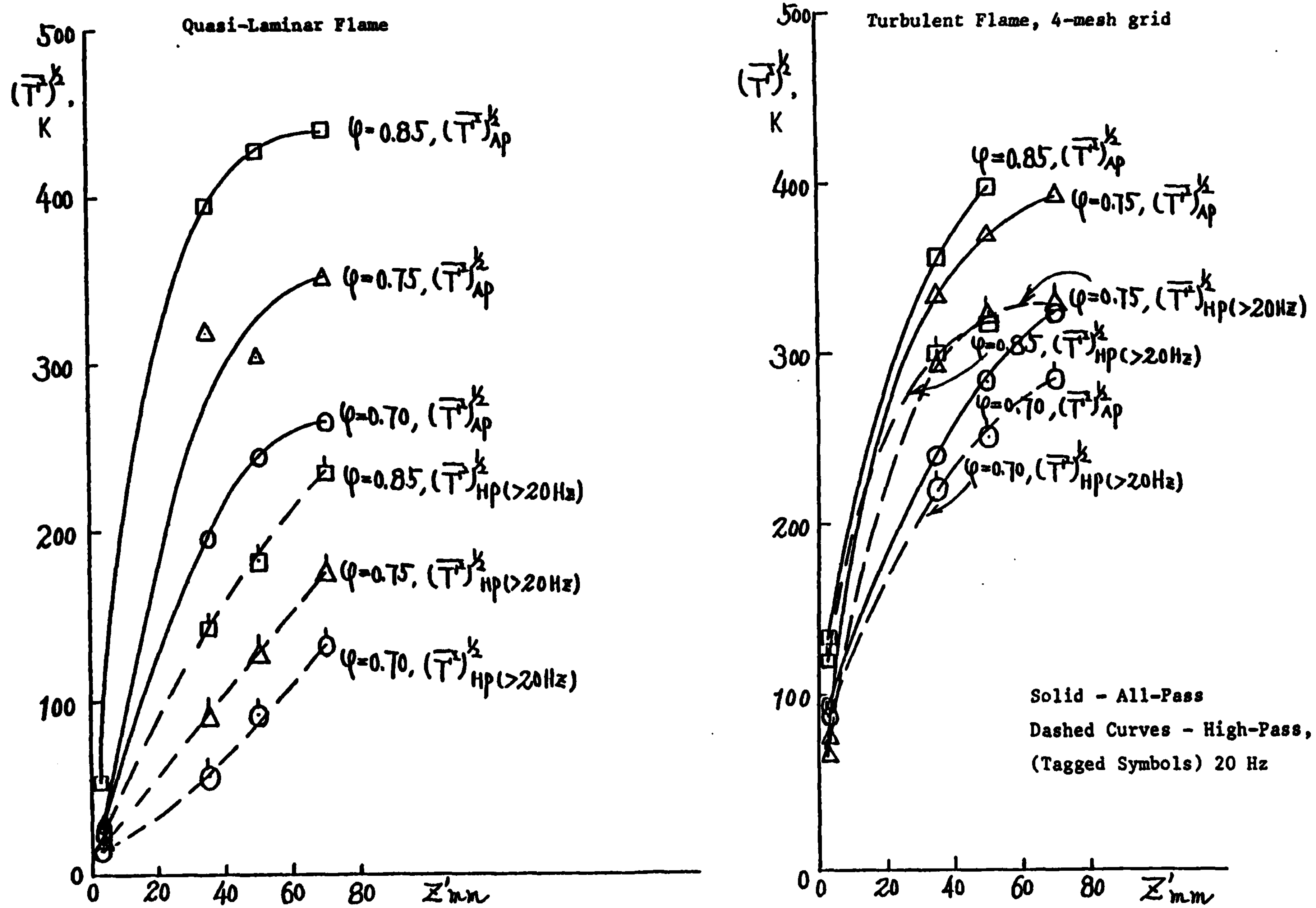


FIG. 6 EFFECTS OF EQUIVALENCE RATIO ON MAXIMUM RMS TEMPERATURE FLUCTUATIONS (ALL-PASS AND HIGH-PASS) AT DIFFERENT DISTANCES FROM THE FLAMEHOLDER FOR QUASI-LAMINAR AND TURBULENT FLAMES

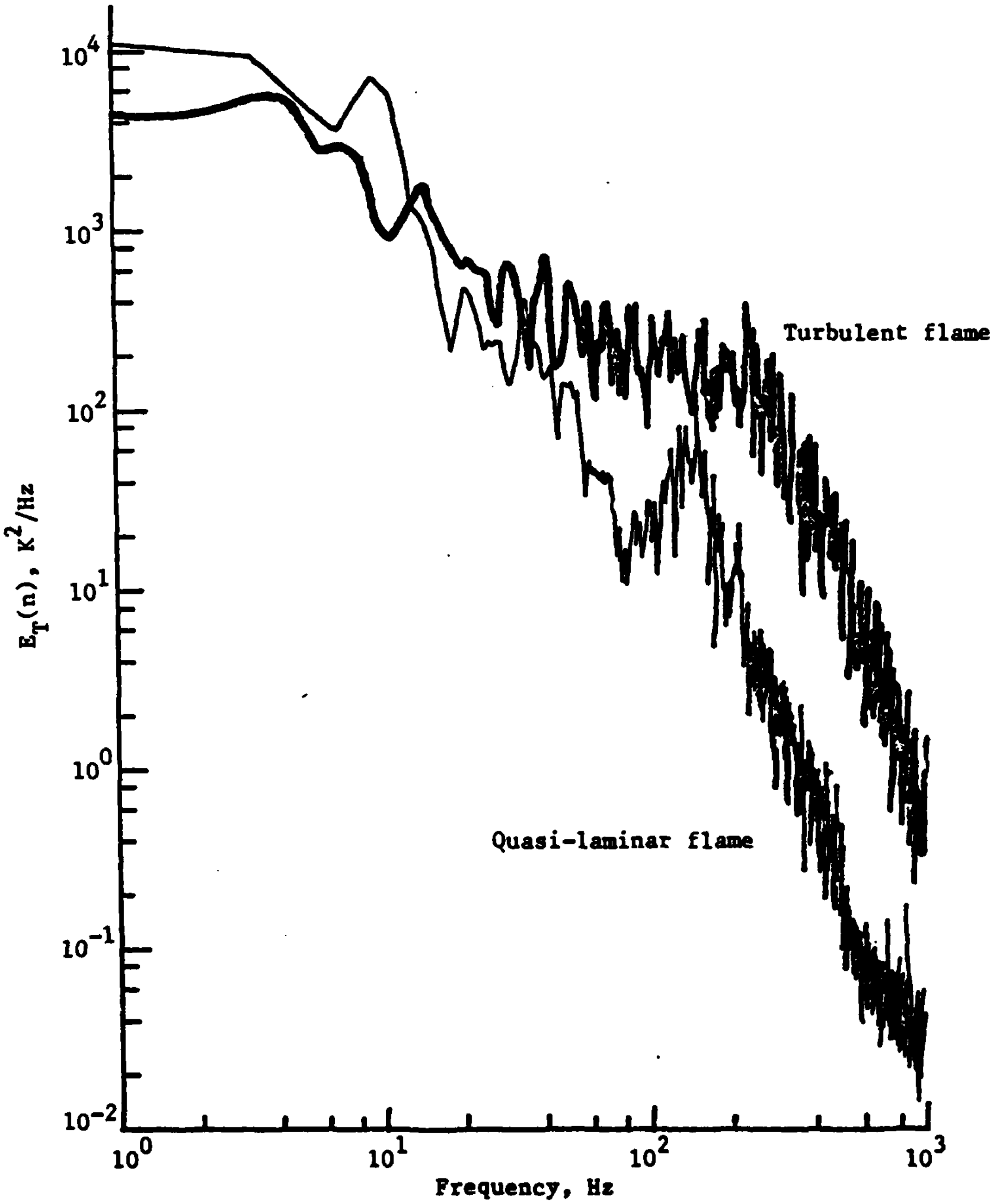


FIG. 7 SPECTRAL DENSITY DISTRIBUTION OF MEAN-SQUARE TEMPERATURE FLUCTUATIONS FOR QUASI-LAMINAR AND TURBULENT FLAMES WITH 4-MESH GRID 35 mm DOWNSTREAM OF FLAMEHOLDER (MAXIMUM RMS TEMPERATURE FLUCTUATIONS, ϕ = 0.75)

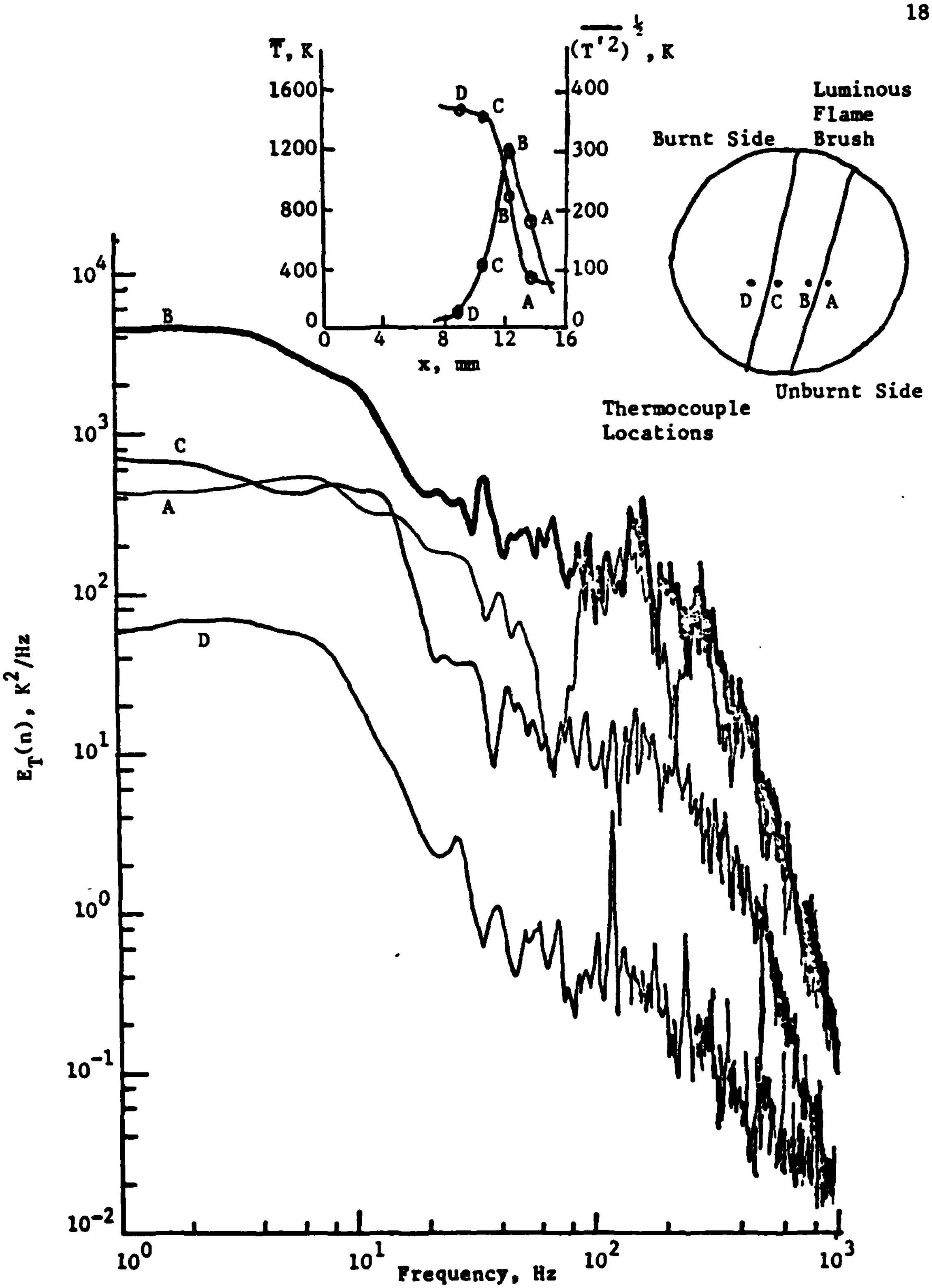


FIG. 8 SPECTRAL DENSITY DISTRIBUTION OF MEAN-SQUARE TEMPERATURE FLUCTUATIONS AT DIFFERENT POSITIONS IN A TURBULENT FLAME WITH 10-MESH GRID (35 mm DOWNSTREAM, ϕ = 0.75)

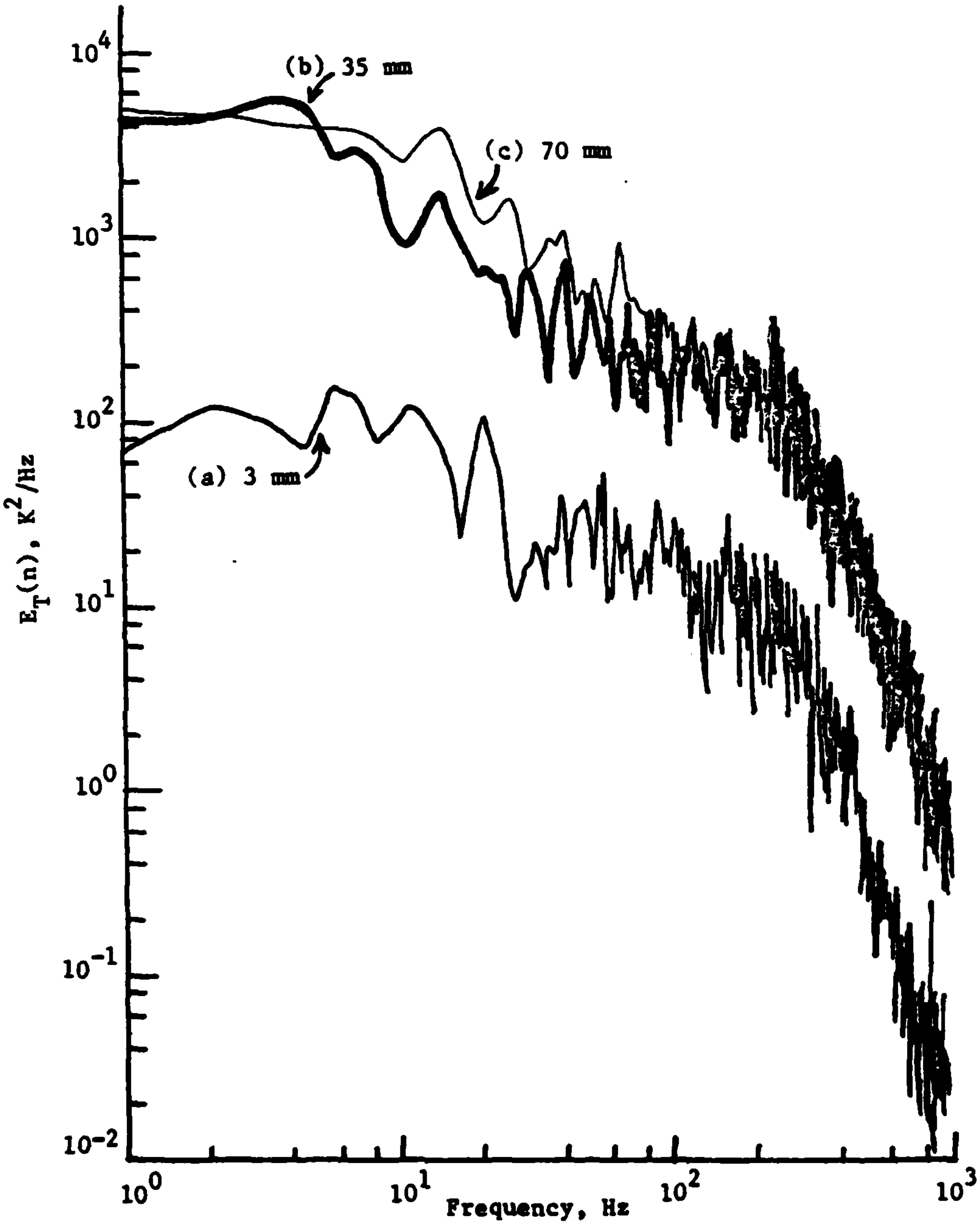


FIG. 9 SPECTRAL DENSITY DISTRIBUTION OF MEAN-SQUARE TEMPERATURE FLUCTUATIONS FOR TURBULENT FLAME WITH 4-MESH GRID AT DIFFERENT DISTANCES DOWNSTREAM OF FLAMEHOLDER (MAXIMUM RMS TEMPERATURE FLUCTUATIONS, ϕ = 0.75)

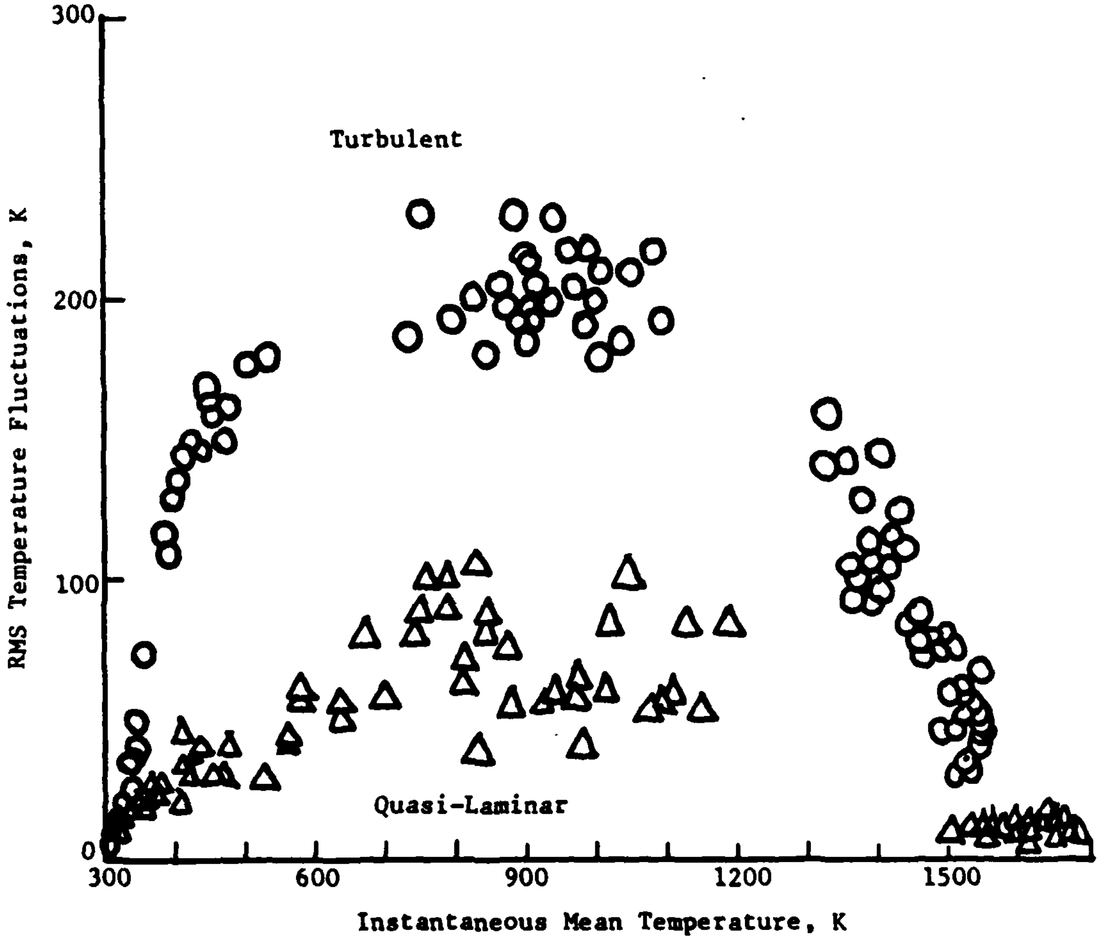


FIG. 10 RMS TEMPERATURE FLUCTUATIONS WITHIN HIGH-FREQUENCY REGION AT DIFFERENT INSTANTANEOUS MEAN TEMPERATURES FOR A TURBULENT FLAME (WITH 4-MESH GRID) AND A QUASI-LAMINAR FLAME (WITHOUT GRID-GENERATED TURBULENCE); 35 mm DOWNSTREAM OF FLAMEHOLDER, 0.75 EQUIVALENCE RATIO AND 2.4 m/s MIXTURE VELOCITY

APPENDIX I

BIBLIOGRAPHY

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APPENDIX II

(1) Scientific Personnel

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Dr. G.E. Abouseif, Co-Investigator

Mr. V.G. Filipenco, Research Assistant

Mr. A. Sharoni, Research Assistant

Mr. X.Q. Zhang, Visiting Scholar

(2) Advanced Degree Awarded

A. Sharoni Sc.D. Department of Mechanical Engineering, M.I.T., May 1983

"An Experimental Study of Turbulence-Combustion Interactions"

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